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SEISMIC ANALYSIS OF ECCENTRIC BUILDING STRUCTURES BY MEANS OF A REFINED ONE STOREY MODEL

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SUMMARY

A refined one-storey model has been developed which is able to evidence effects of interaction phenomena between axial and lateral forces in vertical resisting elements on torsional response of plan asymmetric building structures.
Previous research has shown that influence of inelastic interaction is significant, leading to larger peak ductility demands and, mainly, to larger plan-disuniformity of demands in resisting elements.
In this paper, the new model is used to re-evaluate, in the light of interaction phenomena, the performances of plan asymmetric system designed according to torsional provisions of the European code Eurocode8, in order to asses its suitability regarding torsional specification.

INTRODUCTION

In past years, the adequacy of torsional provisions from some seismic codes, such as the Eurocode 8, have been widely investigated by means of single one-storey models. Extensive parametric dynamic analyses conducted with such type of models have led to evidence that system designed according to Eurocode 8 requirements often exhibit unsatisfying performances [1]. In fact, the Eurocode 8 design specifications on strength of vertical resisting elements leads systems to experience high ductility demands and damage.

Nevertheless, simplified one-storey models used so far neglect important effects that may influence inelastic behaviour of resisting elements and, in turn, of the entire structure. Namely, they are not capable to take into account effect of inelastic interaction between axial and lateral forces in resisting elements, since they sustain uni-directional horizontal forces only.

Moreover, no allowance for vertical forces due to gravity loads and to vertical input ground motions was usually made in the above-mentioned analyses. Conversely, in recent years, some seismic events whose epicenters were located near to large cities (as Kobe earthquake of 1995) as well as the growth and spread of earthquake recording nets have pointed out that vertical components can be severe enough to cause structural damage by themselves or at least to increase damage due to horizontal components only. Therefore, due to their possible effects on torsional response, verifying performances of structures under both horizontal and vertical components appears important.

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As regards vertical forces due to gravity loads, previous papers by the Authors [2] [3], dealing with system not designed for torsional coupling, have clarified that in some circumstances they may influence to a large degree response of asymmetric structures. This happens primarily for mass-eccentric systems for which asymmetric distributions of mass lead to an asymmetric distribution of axial forces in resisting elements, so that they may present different lateral strength capacity because of the influence of interaction phenomena.

For these reasons, a refined model capable to overcome the above limitations, is used in this paper, to re-evaluate the performances of plan asymmetric system designed according to torsional provisions of the Eurocode 8, in the light of interaction phenomena and considering both gravity loads in vertical resisting elements and earthquake vertical components.

The study of code-designed systems according to the Eurocode 8 requirements has been performed for both stiffness-eccentric systems and mass-eccentric ones. The analyses lead to clarify the adequacy of the code in controlling maximum ductility demand and uneven plan-distribution of ductility among resisting elements.

MODEL SPECIFICATION

In this section the main characteristics of the numerical model used in this paper are shown. The model represents an enhancement of single-storey plan asymmetric models considered in previous studies on torsional response, as important refinements have been introduced.

As single-storey plan asymmetric models used so far, even the new model represent a single floor slab sustained by vertical resisting elements. It is assumed that total mass M is distributed over the floor slab and that resisting elements are massless. Nevertheless, contrary to previous models, which have been developed under the assumption that resisting elements are capable to sustain uni-directional horizontal forces only, vertical elements are assumed to provide stiffness and strength along any direction.

Going more into detail, it is assumed that the floor slab is infinitely rigid in its own plane, while it is flexible in the orthogonal direction. As a consequence, the system moves in the horizontal plane as a rigid body, having three degrees of freedom, namely x- and y- translations of the mass centre and floor rotation about vertical axis; furthermore, since floor slab is flexible in the vertical direction, displacements in the z-direction at locations of resisting elements, u_{zi}, are independent. Therefore, on the whole, the structure motion is described by $3+n$ displacement coordinates, being n the number of the resisting elements (Figure1). In this manner, both axial forces due to gravity loads and inertial forces arising from vertical accelerations at the resisting elements locations can be taken into account.

Moreover, horizontal inertia forces and torsional moments involve system total mass M and rotational mass, whereas, due to out-of-plane flexibility of the floor slab, inertia forces resulting from the z-direction accelerations at locations of resisting elements need to be specified; in this paper, for the sake of simplicity, vertical mass m_{zi} for the *i-th* element has been evaluated based on its tributary area.

As previously specified, resisting elements are assumed to provide stiffness and strength along any direction. In order to describe their behaviour in the inelastic range, interaction phenomena are accounted for by means of an ellipsoidal yield domain, as shown in Figure 2, and an elastic perfectly plastic constitutive relationship according to the normality rule has been considered. The ellipsoidal domain of

the *i-th* resisting element is defined once element strengths F_{oxi}, F_{oyi} and F_{ozi}, along the three *x*-, *y*- and *z*-directions respectively, are assigned.

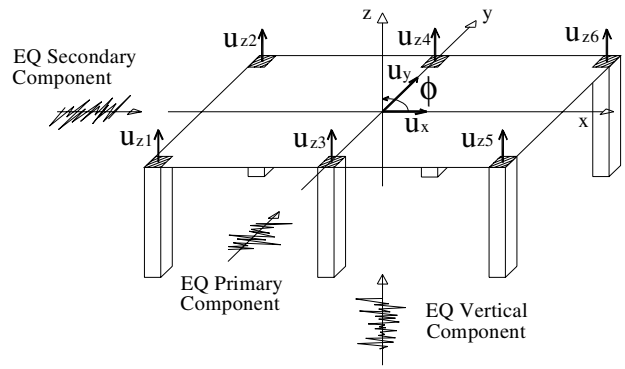

Figure 1: Refined model of asymmetric one-storey structure used in the analyses.

According to the assumed constitutive relation, if the structure is in the elastic range, the three dynamic equilibrium equations, describing motion of floor slab in the horizontal plan, are coupled because of the asymmetry of the structure, but they are uncoupled from the *n* dynamic equilibrium equations in the vertical direction; in the inelastic range, even horizontal and vertical equilibrium equations couple because of the ellipsoidal domain.

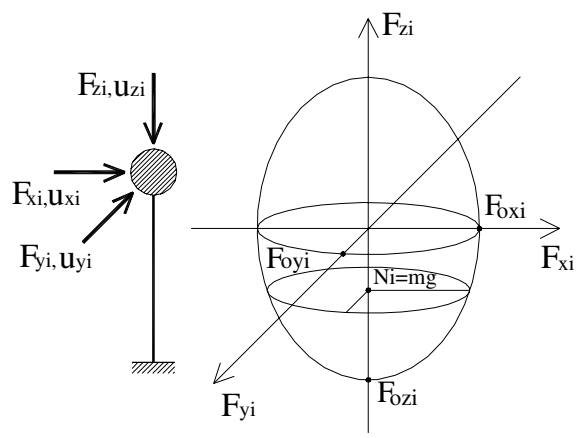

Figure 2: Force-displacement relationship of the *i-th* resisting element.

In order to understand results presented below, it should be recalled that, contrary to the new model presented herein, the previous ones always neglect vertical forces and do not consider dynamic equilibrium equations in vertical direction.

STRUCTURAL SYSTEMS

Two classes of eccentric systems were analysed: stiffness eccentric models and mass eccentric ones. They represent floor slab sustained by six vertical resisting elements located in plan and numbered as shown in

Figure 3. They are one-way eccentric systems, being symmetric in mass, stiffness and strength with respect to the horizontal *x*-axis.

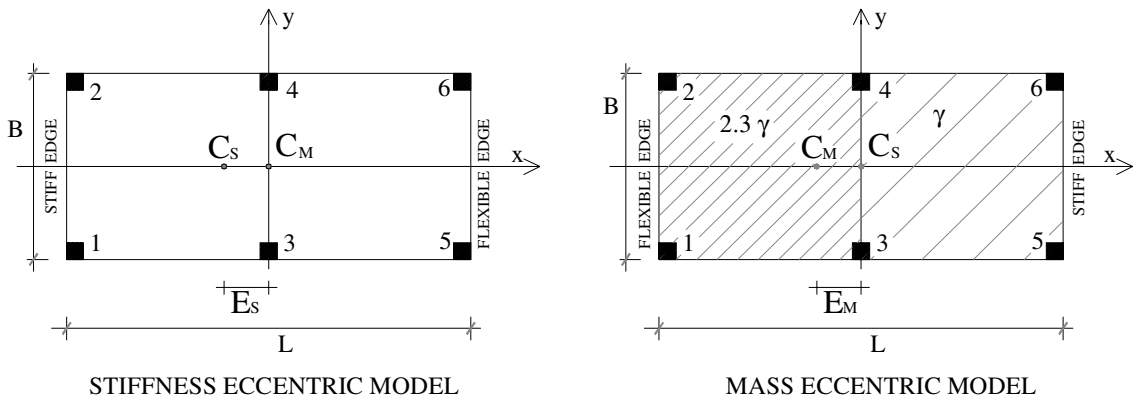

Figure 3: Analysed systems.

In the parametric analysis, for both classes, lateral uncoupled periods in *x*- and *y*- direction $T_x = T_y$ have been varied between 0.1s and 1.5s. Besides, total vertical period T_z has been evaluated from the lateral ones by means of a relation given in Como *et al.* [4] which has been seen to correlate well vertical to lateral period of real building structures, whose vertical stiffness is quite higher than the lateral one. Total lateral and vertical stiffnesses, K_x , K_y and K_z have been derived from the considered T_x, T_y and T_z, respectively. Subsequently, they have been distributed among resisting elements for stiffness-eccentric and mass-eccentric systems as specified later.

Stiffness eccentric systems

As previously mentioned, the analysed systems are assumed to be one-way plan asymmetric, being the center of stiffness centre C_S shifted at a distance E_s (stiffness eccentricity) from the center of mass C_M along the *x*-axis, due to the asymmetric plan distribution of k_{yi}s. Plan distribution of the *x*-stiffnesses, instead, is symmetric, as *x*-stiffness of Element 1, 3, 5 (see Figure 3) is assumed equal to that of Element 2, 4, 6 respectively. For the above-mentioned eccentricity, the widely assumed value of $E_s=0.10L$ has been chosen, being $L = 30$ the floor *x*-plan dimension. Therefore, total lateral stiffness, for each lateral period considered, have been distributed in such way to obtain the desired eccentricity.

Besides, total mass *M* is uniformly distributed over the floor slab. Mass radius ρ, non-dimensionalized with respect to *L,* has been taken equal to $\rho = 0.33$. Ratio of torsional stiffness radius *d* to mass radius ρ has been selected a value of $d/\rho = 1.2$ characterizing the analysed systems as torsionally-stiff. As evaluated from tributary areas, vertical masses at Elements 1, 2, 5 and 6 are equal to *0.125M*, while vertical masses at Element 3 and 4 are equal to *0.25M*.

As regards vertical stiffness assumption, K_z has been distributed among resisting elements, assuming that cross-section areas have been designed proportionally to tributary areas, so that vertical stiffness of Elements 3 and 4 is twice as much as that of Elements 1, 2, 5 and 6.

According to the Eurocode 8 requirements, lateral strengths F_{oxi} and F_{oyi} of each vertical resisting element have been determined by means of a modal response spectrum analysis. Since the modal analysis is conducted under the assumption of linear elastic behaviour, and with the aim of designing only lateral strengths, it can be applied only to the three dynamic equilibrium equations describing motion of floor

slab in the horizontal plan, neglecting the n dynamic equilibrium equations in the vertical direction, certainly uncoupled from the first ones in the elastic range.

Therefore, by assuming the generalized coordinates of displacement shown in Figure 1, squared frequencies of vibrations in x-y plan are:

$$\varpi_1^2 = \frac{K_x}{M}, \qquad \varpi_{2,3}^2 = \frac{K_r + K_y\rho^2 \pm \sqrt{K_y^2\rho^4 + K_r^2 - 2K_rK_y\rho^2 + 4E_x^2K_y^2\rho^2}}{2M\rho^2},$$

where K_r is the torsional stiffness with respect to C_M. Once the corresponding modal shape vectors $\mathbf{\Psi}_J$ are evaluated, modal analysis have been conducted for each relevant direction (x and y) of the structures, since the building model is spatial.

Therefore, for each direction of analysis, denoted as g_j the participation factor, the components in x-y plane of the j-th displacement vector $\mathbf{u}_j^T = \{u_x, u_y, \phi\}$ related to the j-th mode have been evaluated as

$$\mathbf{u}_j = \mathbf{\Psi}_j g_j \frac{S_a(T_j)}{\varpi_j^2},$$

As regard the acceleration design spectrum S_a, the one proposed by the Eurocode 8 for spectrum Type 1 and for soil Type B, has been selected introducing a behaviour factor q equal to 5, in order to design systems that are expected to undergo large inelastic behaviour. Peak ground acceleration a_g has been supposed equal to 0.35g.

Therefore, displacements of the i-th vertical resisting element in x and y direction u_{xi}^j and u_{yi}^j related to the j-th displacement vector $\mathbf{u}_j$ have been evaluated on the basis of the assumption of rigid diaphram of the floor slab. It should be noted that, as the analysed systems are asymmetric only in the y-direction, seismic action applied in x-direction do not induce displacement of resisting elements in y-direction. Subsequently, the maximum value of the displacement u_{yi} of the i-th vertical resisting element is due to the y-seismic action only. It has been evaluated as the root of the sum of u_{yi}^j squared, where u_{yi}^j denotes the displacement due to the j-th vibration mode.

Conversely, for the displacement in x–direction of the i-th resisting element, the effects of the contemporaneous action of the earthquake in the two direction has been evaluated as:

$$u_{xi} = \sqrt{u^2{}_{xi}(y) + u^2{}_{xi}(x)},$$

where $u_{xi}(y)$ and $u_{xi}(x)$ are the effect of seismic force acting in y-direction and x-direction, respectively. Finally, lateral element strengths F_{oxi} and F_{oyi} have been assigned equal to $F_{oxi} = k_{xi}\, u_{xi}$ and $F_{oyi} = k_{yi}\, u_{yi}$.

Besides, as regards vertical element strengths, F_{ozi} has been assigned by applying a safety coefficient $s = 3$ against gravity loads that are expected to act on each vertical element (i.e. $N = 0.125Mg$ for Elements 1, 2, 5 and 6, $N = 0.25Mg$ for Element 3 and 4), a value that is typical of many real structures.
It should be noted that the chosen design criterion for vertical strength leads the ratio between N_i and F_{ozi} to be equal for all resisting elements. Actually, in real structures it may often occur that this ratio would differ from one element to the others, since code specifications regarding other requirements, such as drift limitations, which are not considered in this paper, affect strongly design of structural members.

Mass eccentric systems

As regards mass-eccentric systems, total mass M has been distributed nonuniformly over the floor slab, being mass density on the right side of floor slab γ smaller than that on the left side, taken equal to 2.3γ. As a consequence, the system mass centre C_M is shifted at a distance $E_M = 0.10L$ along the x-axis from the

geometric centre of the floor slab, corresponding with stiffness centre C_S, as shown in Figure 3. Mass radius ρ has again been taken equal to ρ =*0.33*.

As regards masses acting in vertical direction, which are obtained from tributary areas, masses of Element 1 and 2 are $m_{z1} = m_{z2} = 0.175M$, masses of Element 3 and 4 result $m_{z3} = m_{z4} = 0.25M$ and $m_{z5} = m_{z6} = 0.075M$. Therefore, axial forces are larger in Elements 1 and 2 than in Elements 5 and 6, so that their plan distribution in resisting elements is asymmetric (i.e. $N_1 = N_2 = 0.175Mg$, $N_5 = N_6 = 0.075Mg$).

Element stiffness of mass-eccentric systems are symmetric with respect to the floor geometric centre, i.e. it has been assumed that structure is pre-designed for total mass uniformly distributed over the floor slab. Therefore, cross-section areas of Elements 1 and 2, equal to those of Elements 5 and 6, are supposed to be half of those of Elements 3 and 4: as a consequence, lateral stiffness in the *x*- and *y*-direction as well as vertical stiffness of Elements 3 and 4 are greater than those of Elements 1, 2, 5 and 6. Denoting lateral stiffness in *x*- and *y*-direction of the *i-th* resisting element with k_i and its vertical stiffness with k_{zi}, it has been assumed that $k_3 = k_4 = 4k_1 = 4k_2 = 4k_5 = 4k_6$ and $k_{z3} = k_{z4} = 2k_{z1} = 2k_{z2} = 2k_{z5} = 2k_{z6}$, for distributing total stiffnesses, $K_x = K_y$ and K_z. It should be noted that, for the obtained stiffness distribution, the ratio between torsional stiffness radius *d* to mass radius ρ is equal to 1.22, being the system again torsionally-stiff.

Even in this case, design of lateral strengths F_{oxi} and F_{oyi} of each vertical resisting element have been conducted in the same way as for stiffness eccentric systems. The squared of natural frequencies, for these systems, are given by

$$\varpi_1^2 = \frac{K_x}{M}, \qquad \varpi_{2,3}^2 = \frac{K_r + K_y(\rho^2 + E_M{}^2) \pm \sqrt{K_r^2 - 2K_rK_y(\rho^2 - E_M{}^2) + K_y^2(\rho^2 + E_M{}^2)^2}}{2M\rho^2};$$

modal response spectrum analysis has been conducted analogously to that shown for stiffness-eccentric systems, with the relevant modal shape vectors and participation factors.

Element vertical resisting strength F_{ozi} has again been set by amplifying gravity load by the same safety coefficient $s = 3$; therefore, given the described plan-distribution of axial forces, vertical strengths of Elements 1, 2 are $F_{oz1} = F_{oz2} = 0.175Mg*s$, while $F_{oz3} = F_{oz4} = 0.25Mg*s$ and $F_{oz3} = F_{oz4} = 0.075Mg*s$. Therefore, also in this case of no uniformly plan-distribution of axial forces, ratio F_{ozi}/ N_i has been assumed equal for all resisting elements.

DYNAMIC PARAMETRIC STUDY

The designed systems have been subjected to a bi-directional earthquake excitation, even if, for a few cases, also the vertical component has been considered.

The input ground motion selected is an ensemble of five pairs of horizontal components of real earthquakes that can represent, on the average, the seismic excitation adopted by the Eurocode 8. The main characteristics of the selected records are reported in Table 1. For each pair of records, the component having the higher peak ground acceleration (PGA) has been arbitrarily assumed to act along the *y*-direction. The other component has been taken as *x*-direction input. For the Northridge earthquake also vertical component has been used.

Earthquake	Date	Station	Duration (sec)	Primary component PGA (g)	Secondary component PGA(g)
Imperial Valley	18.05.40	El Centro	53.40	0.348	0.214
Kern County	21.07.52	Taft	54.40	0.179	0.156
Montenegro	15.04.79	Petrovac	19.60	0.438	0.305
Valparaiso	03.03.85	El Almendral	72.02	0.284	0.159
Northridge	17.01.94	Newhall	59.98	0.590	0.583

Table-1: Earthquake records used as input ground motion

As regards damping ratio, for all the analyses, a value of 5% for the first two modes of vibration has been considered.

RESULTS

In this investigation, prediction of seismic performances of the Eurocode8-designed systems has been evaluated considering axial forces in resisting elements and interaction phenomena, as given by the new model, and it has been compared to that obtained in previous analyses, i.e. neglecting both the above-mentioned aspects.

The analysis has been carried out in order to clarify the effect of Eurocode 8 design criteria in terms of inelastic demands and of structural damage of resisting elements, in the light of the influence of the phenomena under investigation.

First of all, as regards the choice of damage parameter, it should be noted that the definition of element force-displacement relationship and the use of bi-directional excitation requires the introduction of proper indicators for measuring a multi-directional inelastic action. Therefore, it has been selected a parameter that represents an extension of the well known displacement ductility demand, which is usually considered to measure damage under uni-directional action. Namely, it has been computed the so-called radial ductility μ_{rad}, given by the maximum ratio between the modulus of displacement vector and that of yield displacement vector in the same direction:

$$\mu_{rad} = \max\left(\frac{u_x(t)^2}{u_{ox}^{\ 2}} + \frac{u_y(t)^2}{u_{oy}^{\ 2}} + \frac{u_z(t)^2}{u_{oz}^{\ 2}} \right)^{\frac{1}{2}}$$

The maximum radial ductility demand reached during earthquake excitation among all resisting element have been evaluated and denoted as RD_{max}. Figure 4 shows results for stiffness- and mass-eccentric systems. Plots represent the mean values of RD_{max}, averaged over the five input considered, as a function of the lateral uncoupled period T. Results show that peak of ductility demand are very high, especially in the low-medium range of period.

Moreover, in order to evidence differences with results of analysis conducted by means of previous simplified model and isolate the influence of interaction phenomena and the presence of axial loads on ductility demand, values of RD_{max} have been divided by the maximum radial ductility demand of the same system obtained without considering interaction phenomena. The obtained quantity has been denoted as Rda_{max}. Graphs represented in Figure 5 show the mean values of Rda_{max}, considering or not the presence of gravity loads.

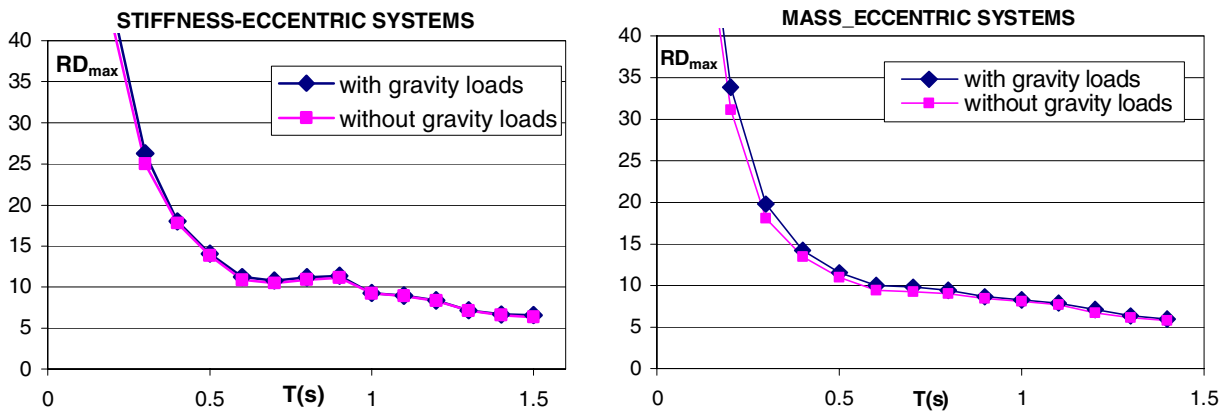

Figure 4: Mean values of peak of radial ductility demand RD_{max} vs lateral uncoupled period T.

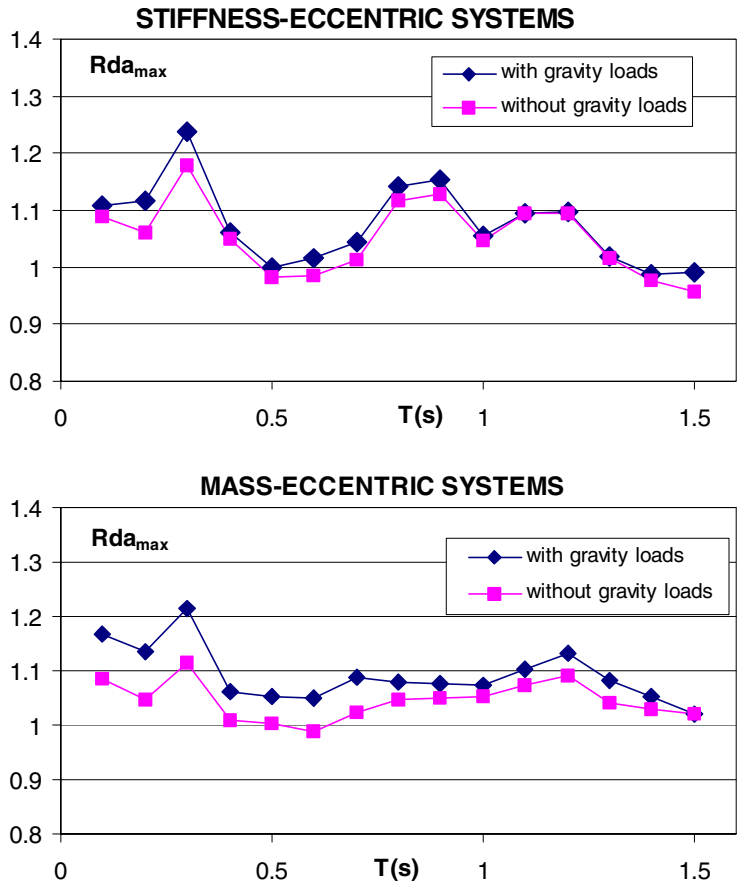

Figure 5: Mean values of Rda_{max} vs T, denoting differences with respect to previous analyses neglecting interaction phenomena.

Results show that previous analyses, in which interaction phenomena were neglected, underestimate the maximum ductility demand, as evidence trend of parameter Rda_{max}, almost always grater than the unity.

Few results obtained applying the Northridge records only show that vertical component does not induce significant variations on RD_{max} parameter with respect to response obtained by means of the model under bi-directional horizontal excitation only.

Furthermore, in order to estimate plan distribution of ductility demands among resisting elements as evaluated by the two models (i.e. with and without interaction phenomena) radial ductility demand μ_{rad} is carried out for each resisting element.

Figure 6 represents curves of radial ductility for all resisting elements (numbered as shown in Fig.1 and denotes here as Elem.1 – Elem.6), as a function of lateral uncoupled period T

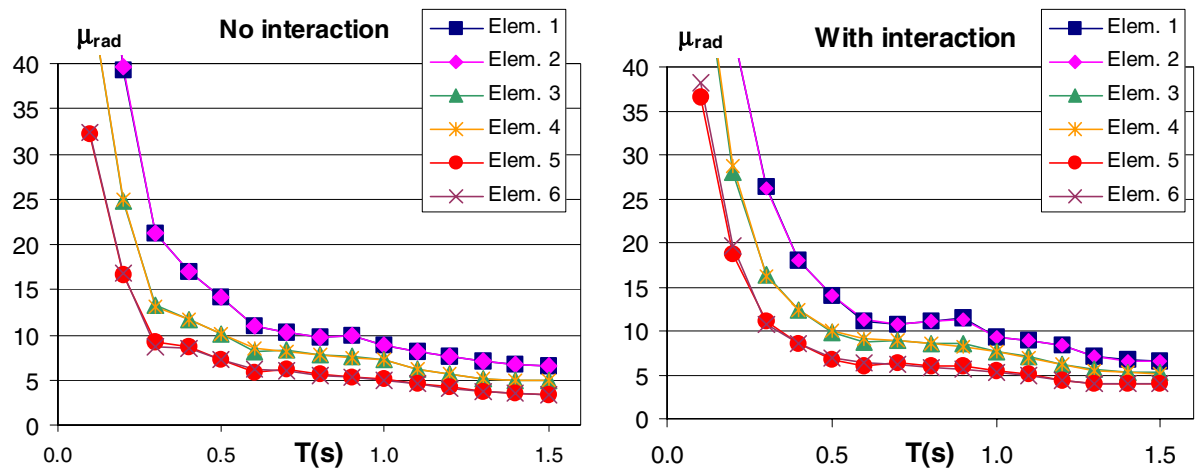

Figure 6: Mean values of ductility demand in resisting elements for stiffness-eccentric systems.

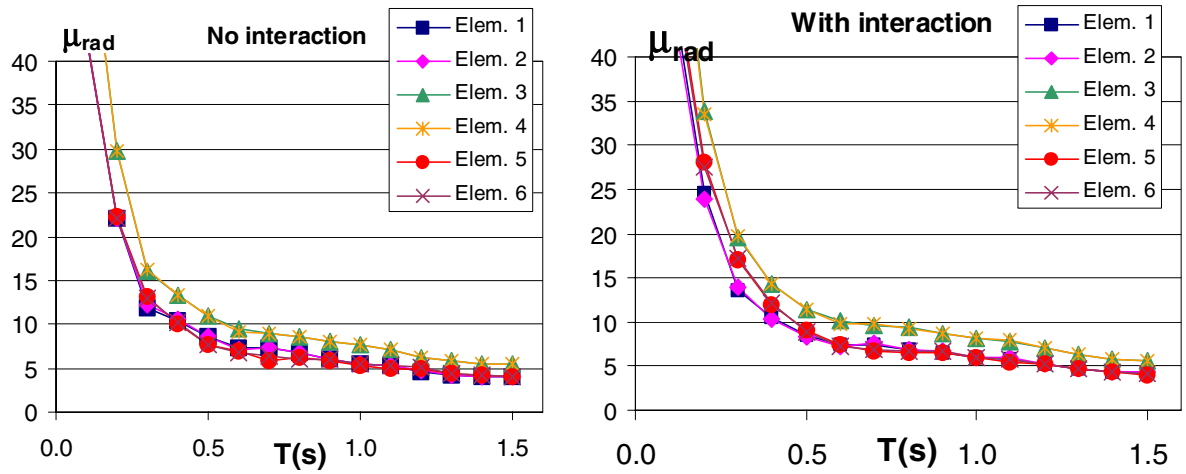

Figure 7: Mean values of ductility demand in resisting elements for mass-eccentric systems.

For stiffness-eccentric systems, Figure 6 evidence that, as regard plan-distribution of ductility demand, results obtained with the developed model confirm those obtained previously: high values of ductility demand are drawn by Element 1 and 2, located at the rigid-side, while Element 5 and 6 at the flexible-side are subjected to lower inelastic demands.

For mass-eccentric systems, instead, trends are not completely in agreement. Even if ductility demands of Element 3 and 4 located at the centre of the floor slab are always the largest, both considering or not interaction phenomena and gravity loads, predictions of ductility demand distribution between the rigid side and the flexible one are different. Variations are certainly correlated with the asymmetric plan-distributions of axial forces in resisting elements, even if the simple design criteria adopted for the analysed systems – for which ratio between vertical strength and vertical loads is symmetric – reduce significantly these effects. It should be recalled, as a matter of fact, that real building very often present different safety levels with respect to vertical forces in resisting elements with a possible higher effect on plan distribution ductility demands. Therefore, further investigation is needed in order to assess behaviour of more realistic building models.

CONCLUSIONS

In this paper, stiffness eccentric and mass eccentric building designed according to the current Eurocode 8 torsional provisions have been analysed in order to asses their performances. The study has been conducted by means of a enhanced one-storey asymmetric model, through which some important refinements, with respect to models of the same type used so far, are introduced.

The new idealization can take into account the presence of vertical forces due both to gravity loads and to vertical input ground motion as well as the effects of inelastic interaction between axial forces and bi-directional horizontal forces, allowing to capture their influence on torsional response.

Results of the analysis confirm that design criteria proposed by the Eurocode 8 for lateral strength in resisting elements are unsatisfactory, leading systems to experience large values of maximum ductility demand with significant variations over the building plan. Moreover, due to interaction phenomena, the model used herein evidences values of ductility demands higher than those obtained by simplified models, with a further little amplification when also gravity loads in resisting elements are considered.

As regard plan-distribution of ductility demands among resisting elements, results obtained in this study substantially confirm those obtained in the previous ones. It should be underlined, however, that plan-distribution is certainly correlated to the different levels of axial forces in resisting elements with respect to vertical strengths, here neglected but often present in real buildings for which further investigations are recommended.

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